REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
26-09-2002	Final Report	20 September 2000 - 31-Aug-02

4. TITLE AND SUBTITLE

Investigating Strain Path Changes on Flow Stress and Microstructure Evolution in Ti-6Al-4V alloy during Hot Deformation

5a. CONTRACT NUMBER
F61775-00-WE063

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Professor John Beynon

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The University of Sheffield
Sir Robert Hadfield Building
Mappin Street
Sheffield S1 3JD
United Kingdom

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0014

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
SPC 00-4063

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Using the purpose built arbitrary strain path rig, hot deformation testing has been carried out on a commercial Ti-6Al-4V alloy. Initially, simple reverse torsion tests were performed, followed by tests combining torsion and uniaxial deformation. Optical and scanning electron microscopy have been used to assess the initial, heat treated and deformed structures. Bulk texture analysis has been carried out on the initial material, Electron Beam Backscattering Diffraction (EBSD) was used to assess micro-texture changes in heat-treated and deformed material.

15. SUBJECT TERMS
EOARD, Metals & alloys, titanium alloys

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18, NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS	UL	6	Charles H. Ward, Lt Col, USAF
					19b. TELEPHONE NUMBER *(Include area code)* +44 (0)20 7514 3154

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

Required Statements

"The contractor, The University of Sheffield, hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No F61775-00-WE063 is complete, accurate, and complies with all requirements of the contract.

DATE: 26th September 2002.
Name and Title of Authorized Official: Professor John H. Beynon"

(A) "~~Disclosures of all subject inventions as defined in FAR 52.227-13 have been reported in accordance with this clause~~"
(B) "I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract

DATE: 26th September 2002.
Name and Title of Authorized Official: Professor John H. Beynon"

DISTRIBUTION STATEMENT A:
Approved for Public Release -
Distribution Unlimited

Investigating Strain Path Changes on Flow Stress and Microstructural Evolution in Ti-6Al-4V alloy during Hot Deformation

R.M. Poths, B.P. Wynne, W.M. Rainforth, J.H. Beynon
IMMPETUS Sir Robert Hadfield Building, Mappin Street, Sheffield, S1 3JD, UK.

Summary

Using the purpose built arbitrary strain path rig, hot deformation testing has been carried out on a commercial Ti-6Al-4V alloy. Initially, simple reverse torsion tests were performed, followed by tests combining torsion and uniaxial deformation. Optical and scanning electron microscopy have been used to assess the initial, heat treated and deformed structures. Bulk texture analysis has been carried out on the initial material, with EBSD used to assess micro-texture changes in heat-treated and deformed material.

Initial material

The material was supplied as hot rolled, mill-annealed bar, diameter 30mm, having the composition shown in Table 1. The initial structure comprised equiaxed alpha, having a random texture.

Heat treatment

To obtain a similar starting microstructure to that used by our collaborators, a four step heat treatment was carried out on each sample prior to testing. This comprised: 6 minutes at 815°C, 1 minute at 1040°C, 2 minutes at 950°C and finally 10 minutes at the test temperature, 815°C; for each temperature change a heating rate of 490°C/minute was used. Water quenching following heat treatment showed that this schedule resulted in a colony microstructure with a prior beta grain size of 110μm, a mean alpha lamella thickness of ~1μm and a 2μm thick grain boundary layer of alpha phase.

Hot deformation testing

Isothermal tests were carried out on torsion samples having a gauge diameter of 6.60mm and length 13.20mm, see Figure 1. Two series of hot deformation tests were carried out, the first using forward and reverse torsion, in strain increments of 1 (Table 2). The second series used a torsion pre-strain of 0.33 followed by a combination of torsion/reverse torsion/compression to a total strain of 0.66 (Table 3). Monotonic torsion resulted in a peak flow stress followed by flow softening before steady state stress was reached at strains of ~0.5.

Series 1 – Strain reversal following forward torsion to a strain of 1 resulted in a reduction in the flow stress upon reloading, although difficulties with data recording meant that this could not be accurately quantified at the time. The 0° test was used to obtain a plot of the globularisation kinetics for forward torsion, as shown in Figure 2. This data was measured using point counting methods, from a series of back scattered electron (BSE) images taken at a magnification of x2000 across the diameter of an axial section. Measurements of the fraction globularised were also taken following a 180° strain path change and following a 180°+180° strain path change; these are also shown on Figure 2. In both cases, the globularisation is retarded compared with monotonic deformation. Bends/kinks were observed in the alpha lamellae following a single deformation, but many of these were straightened by a reverse deformation, as shown by the BSE images in Figure 3. Strain reversal also resulted in a coarser globularised grain size.

Series 2 – Figure 4 is an example of the flow curves obtained from the hot deformation tests, illustrating the flow response to a strain path reversal after a strain of 0.33 in torsion. Initially, flow softening is seen, followed by an increased work hardening rate until the steady state stress of the forward torsion test is achieved at the maximum strain. Due to the low torque values

AQ F03-01-0138

associated with the strains/strain rates used in this work, the sensitivity was not sufficient to detect more subtle changes in flow behaviour for strain paths less than 180°. Axial sections were examined using BSE imaging techniques, and in all cases there was some kinking/bending of the alpha lamellae, but the low values of strain used in these tests meant no dynamic globularisation had occurred and any microstructural differences were subtle.

EBSD data from the heat-treated samples and both series of hot deformation samples requires further analysis to ascertain whether or not any significant conclusions can be drawn.

Conclusions

- Strain path reversal resulted in flow softening greater than that seen during monotonic deformation, after both small (0.33) and large (1) pre-strains.
- The kinetics of dynamic globularisation are retarded by strain path reversal, which also results in an apparent straightening of previously bent alpha lamellae, and a coarsening of the globularised grains.
- Morphology changes due to strain path changes of less than 180° were not observed, probably due to the low strains used in this study.

Figures & Tables

Table 1 – Chemical composition (weight percent)

Al	V	Fe	C	N	O	Ti
6.6	4.1	0.14	0.06	0.007	0.2	Bal.

Table 2 – Testing series 1

Strain 1	Strain 2	Strain 3	Strain path angle
Torsion 1	-	-	0°
Torsion 1	Torsion 1	-	0°
Torsion 1	Reverse torsion 1	-	180°
Torsion 1	Reverse torsion 1	Torsion 1	180° + 180°

Table 3 – Testing series 2

Pre-strain	Strain	Strain path angle
Torsion 0.33	Torsion 0.33	0°
Torsion 0.33	Reverse torsion 0.33	180°
Torsion 0.33	Compression 0.33	90°
Torsion 0.33	Compression/reverse torsion 0.33	135°

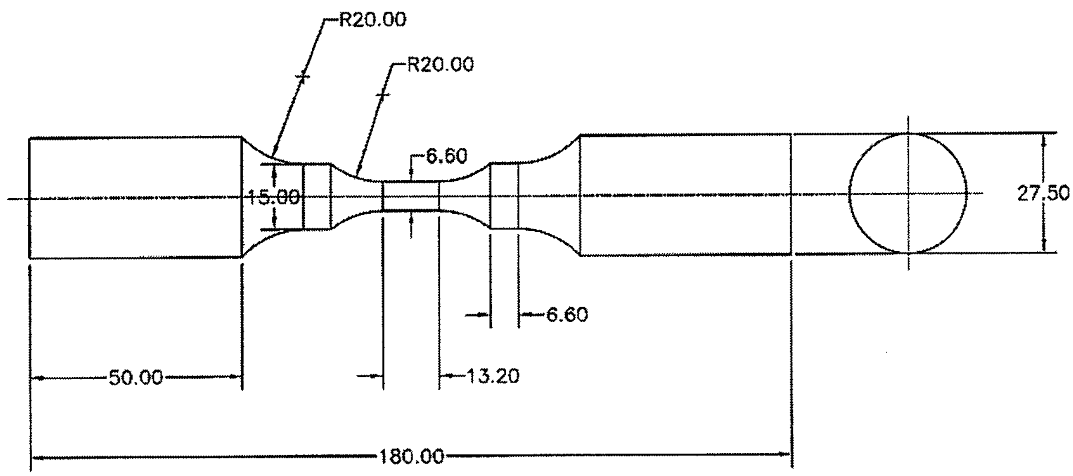


Figure 1 – Diagram showing test piece dimensions in mm, general tolerance ±0.05mm

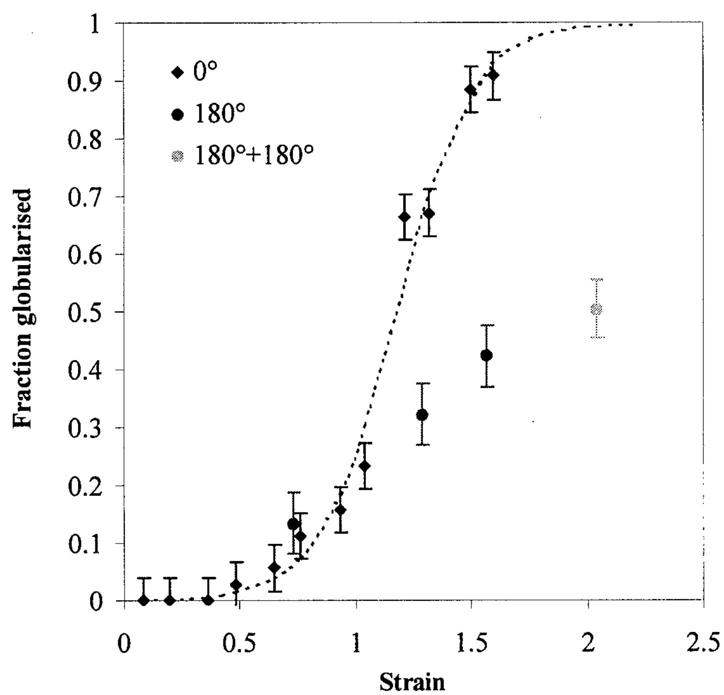
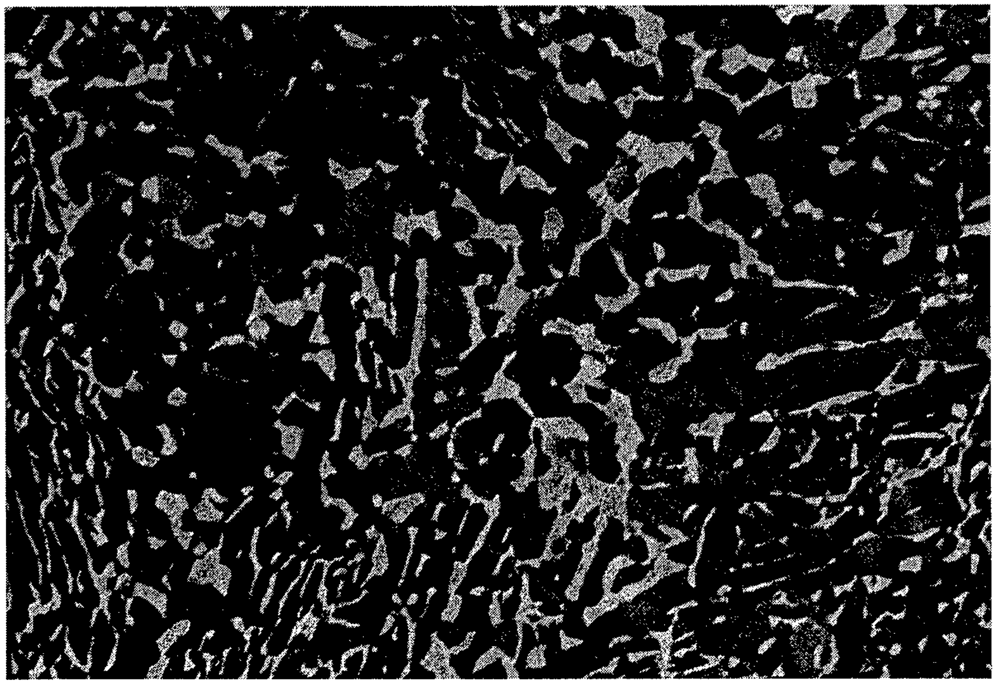
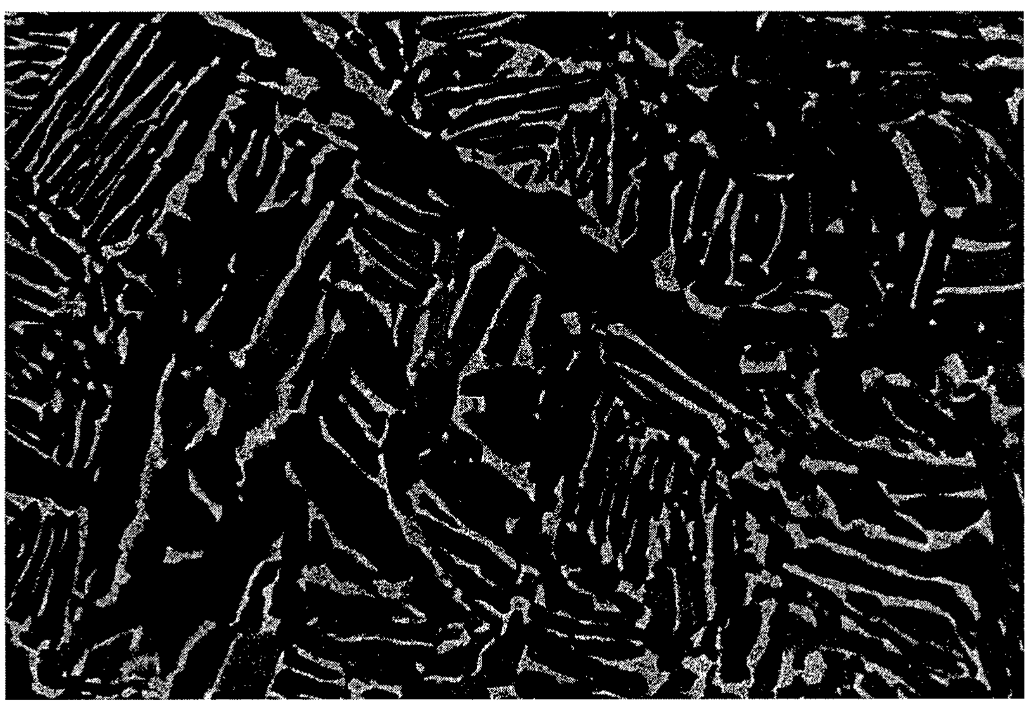


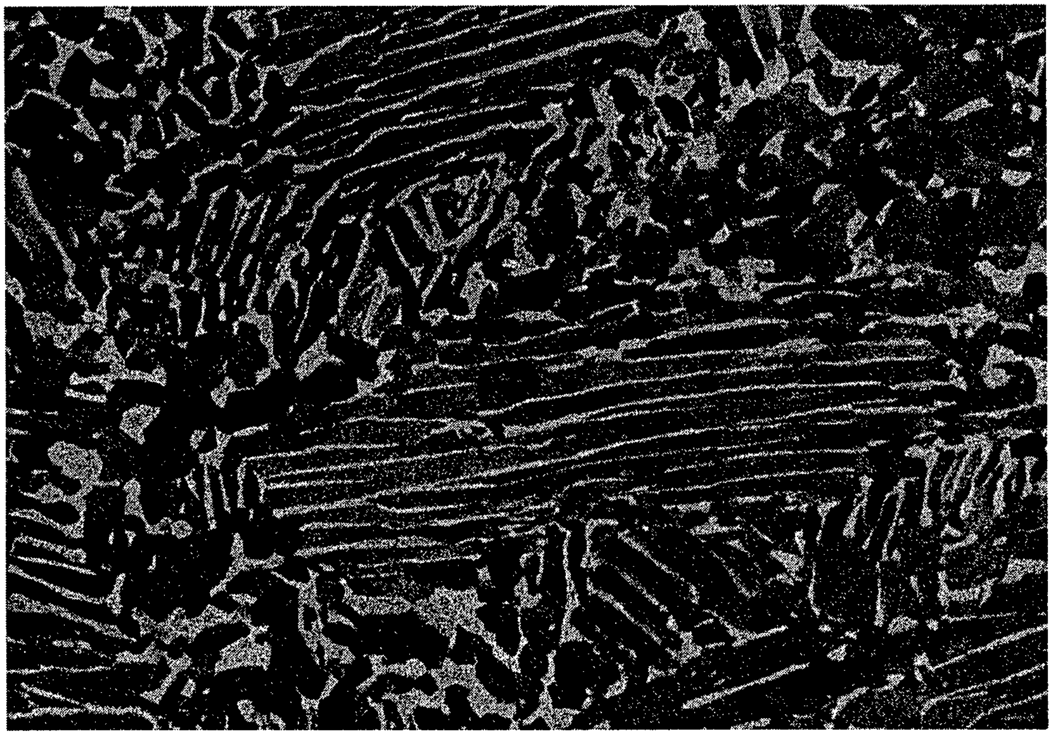
Figure 2 – Globularisation kinetics from series 1, deformed in torsion/reverse torsion at 815°C, at a strain rate of $0.001 s^{-1}$



Monotonic torsion – local strain ~1.3, 66% globularised 10μm



180° strain path change – local strain ~1.3, 32% globularised 10μm



180°+180° strain path change – local strain ~2.0, 50% globularised 10μm

Figure 3 – BSE images of deformed microstructures from series 1, deformed in torsion/reverse torsion at 815°C, at a strain rate of $0.001s^{-1}$

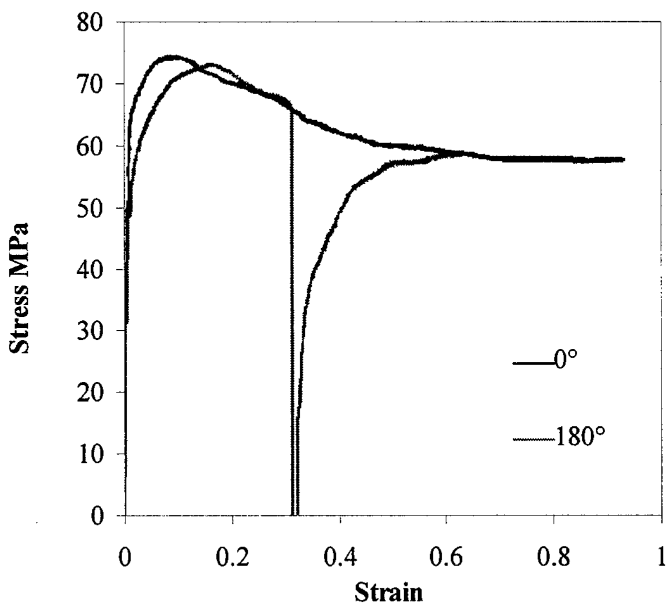


Figure 4 – Flow curves from series 2, deformed in torsion/reverse torsion at 815°C, at a strain rate of $0.001s^{-1}$